# FIBER OPTIC-BASED PROBE FOR USE IN CONDUCTIVE MEDIA

## STATEMENT OF GOVERNMENT INTEREST

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## BACKGROUND

Scour is a severe problem that results in millions of dollars of damage to infrastructure and loss of life annually. Scour occurs during times of high tides, hurricanes, rapid river flow and icing conditions when sediment, including rocks, gravel, sand, and silt are transported by the currents, undermining bridge pier foundations, submarine utility cables and pipelines, and filling in navigational channels. Scour is dynamic; ablation and deposition can occur during the same high–energy hydrodynamic event, so the worst-case net effect cannot be easily predicted nor previously monitored in real-time.

Several bridge scour monitoring technologies exist, including several patented electromagnetic sensors, including U.S. Patent 5,784,338, *Time Domain Reflectometry System for Real-Time Bridge Scour Detection and Monitoring,* to Yankielun, N.E. and L. Zabilansky, July 21, 1998; U.S. Patent 5,790,471, *Water/Sediment Interface Monitoring System Using Frequency Modulated Continuous Wave*, to Yankielun and Zabilansky August 4, 1998; and U.S. Patent 6,084,393, *Scour Probe Assembly*, to Yankielun, July 4, 2000.

These technologies, employing metallic time domain reflectometry (TDR) and frequency-modulated continuous wave FM–CW reflectometry have proved highly successful in detecting, monitoring and measuring scour and deposition of sediments in freshwater. However, they are of limited utility, or even unusable in conductive media such as brackish water, seawater, or in clays and some contaminated soils. Consequently,

the technologies may be deployed only in inland (fresh) bodies of water having sediments comprising non-cohesive (non- clay-based) soils.

Dr. Yankielun developed an optical TDR-based (OTDR) scour probe that relies on "micro-bending" in an optical fiber. This micro-bending is caused by the impinging pressure of sediments on a specially configured optical fiber to indicate the extent of scour depth. The technology is described in U. S. patent 6,526,189, *Scour Sensor Assembly*, to Yankielun, February 25, 2003. While circumventing the problems encountered by conventional metallic TDR in saline waters and cohesive soils, the system uses an expensive OTDR unit.

An embodiment of the present invention employs an optical reflection coefficient-based technique. See U. S. published patent application 20030117154 A1, *Method and Instrument for Electronically Recording and Imaging Representations of the Interaction of an Object with Its Environment*, by Yankielun and J. H. Clark, June 26, 2003, incorporated herein by reference. Using this technique, one may detect, monitor and measure sediment transport in conductive water/sediment environments economically, continuously and in real-time.

This new technology improves the ability to perform sediment transport research, monitoring, and measurement in coastal zones, saltwater estuaries, embayments and other highly conductive waters, especially in cold regions and in the presence of ice. The system is not only applicable to saline and highly conductive environments but will function as well in freshwater regimes.

## BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 depicts the physical geometry of light as it travels from a first medium to a second medium and is reflected back from the second medium as is known in prior art.

Figure 2 shows a clad optical fiber presented normally to the interface between the first and second media of Fig. 1, as is known in the prior art.

Figure 3 is a vertical view of an embodiment of the present invention as it may be installed in a typical configuration.

Fig. 4 is a schematic of an embodiment of the present invention, showing a single optical fiber collector for clarity.

Figure 5 depicts representative circuits that may be used in the schematic of Fig. 4.

Figure 6 depicts fiber optic ports used in an embodiment of the present invention.

Figure 7 shows a display that may be used with an embodiment of the present invention.

Figure 8 depicts an embodiment of the present invention as it would be installed in sediment below a body of water.

Figure 9 depicts an alternative to some of the representative circuits employed in Fig. 5.

## DETAILED DESCRIPTION

In general, a system is provided for monitoring and alerting to change in media. It comprises optical means for sensing change in characteristics of media and transmitting data representing the change; an array of these optical means in which an end of each optical means is affixed to a support having a long axis and each optical means is exposed orthogonal to the media with respect to the long axis; a means for energizing each optical means; a processing means communicating with the optical means; and a means for coupling together the optical means, the energizing means and the processing means. The array may be configured to provide a pre-specified level of detail regarding the change. Real time alerting is associated to the change and information related to the change is displayed and recorded by the processing means. Depending on its application, the system may include a control device and an anchoring device for installation.

An embodiment of the present invention monitors and alerts to change in media adjacent an installed part of the embodiment. It comprises an array of optical fibers affixed to a support, each optical fiber having an end exposed orthogonal to the media; a

source to energize each optical fiber during operation; an optical coupler or splitter for each optical fiber; and a sub-system connected to each optical fiber during operation. The sub-system processes received data to provide real time alerting to the change and records and displays information corresponding thereto. An optical signal is maintained on each optical fiber during operation and the array may be configured to provide a pre-specified level of detail regarding a change.

The change may be indicated by a change in reflection coefficient, transmission coefficient, and combinations thereof. Data transmitted on the optical fibers, as well as the signals that energize the individual fibers, may be multiplexed in a pre-specified sequence.

The sub-system may further include a multi-channel multiplexed data acquisition printed circuit board incorporating an analog-to-digital converter connected to a personal computer having a display and software loadable on the personal computer for processing the data.

In one application, an embodiment of the present invention may be fitted with either or both of a control device and a heavy anchor for buried installation in sediments below a body of water.

A method for monitoring and alerting to change in media is also provided. In one embodiment, the method includes:

providing arrays of optical fibers in which the arrays are each affixed to a support having a long axis;

exposing an end of each optical fiber orthogonal to the media with respect to the long axis ;

configuring each array to provide a pre-specified level of detail regarding the change;

impressing an optical signal from a source on each optical fiber;

collecting the impressed optical signal and a response signal of the media to the impressed optical signal;

providing a sub-system to communicate with each optical fiber such that the sub-system processes the response to enable real time alerting to change and displays and records the change; and

providing a coupler for connecting each optical fiber to the source and the sub-system.

Refer to Figs. 1 and 2. Optical reflection 102 and transmission 101, 103 modes may be employed for the detection and measurement of the change in characteristics of material in contact with the terminal end of an optical fiber as shown at 201 in Fig. 2. In the case of reflection 102, optical principles following Snell's Law apply as follows. At an arbitrary refractive index interface boundary, *ab*, the reflection coefficient, $\rho_{ab}$ is defined as:

$$\rho_{ab} = \left| \frac{\eta_a \cos(\theta_b) - \eta_b \cos(\theta_a)}{\eta_a \cos(\theta_b) + \eta_b \cos(\theta_a)} \right| \tag{1}$$

where:

$\eta_a$ = refractive index of material *a* at the interface boundary *ab*

$\eta_b$ = refractive index of material *b* at the interface boundary *ab*

$\theta_a$ = incident angle (with respect to vertical) of energy (light) in material *a*

$\theta_b$ = refractive angle (with respect to vertical) of energy (light) in material *b*.

Thus, with an incident angle ($\theta_a$ goes to zero) normal to the boundary *ab* and the associated refractive angle ($\theta_b$ goes to zero) that also is normal to the boundary *ab*, the reflection coefficient for an incident wave 101 that is normal to an arbitrary refractive index boundary discontinuity as at *ab* is:

$$\rho_{ab} = \left| \frac{\eta_a - \eta_b}{\eta_a + \eta_b} \right| \tag{2}$$

Complementing the reflection coefficient is the transmission coefficient, $\tau_{ab}$, representing the fraction of light energy that passes through the refractive index boundary *ab*, such that:

$$\tau_{ab} = 1 - \rho_{ab} \tag{3}$$

The relationship 200 between Eqns. (2) and (3) is illustrated in Fig. 2. Thus, the fraction of incident energy that is reflected is dependent on the relative magnitudes of the refractive indices, $\eta_a$ , $\eta_b$, of the two materials that meet at an interface boundary *ab*.

For a sediment scour monitoring implementation using an embodiment of the present invention, the value of $\eta_a$ is fixed as the refractive index, $\eta_f$ , of the fiber optic

transmission medium. The value of the refractive index, $\eta_b$, varies if the *"b"* component of the boundary is water or saturated sediment. Although somewhat temperature dependent, water has a nominal refractive index of $\eta_\omega = 1.3$. Weast, R. C. (ed), CRC Handbook of Chemistry and Physics, CRC Press, Cleveland, OH, 58th edition, 1977. The core of the plastic optical fiber used in an embodiment of the present invention has an index of refraction of $\eta_f = 1.492$. Industrial Fiber Optics, Inc., Product Catalog, Tempe, AZ, 1999. Other optical fibers (either plastic or glass) with different characteristics may serve as well. The refractive index for other optical fibers may vary from this value, but should be selected to be different from that of water. The index of refraction of the sedimentary material that may come in contact with the end of the clad optical fiber varies according to local mineralogy, granularity and packing efficiency as related by the sediment grain structure and the amount of water saturation thereof. The index of refraction from any sedimentary material is generally significantly different from both that of the overlying water and the optical fiber, even water that is muddy from runoff.

Refer to Fig. 3. The fiber optic scour sensor 300 consists of a vertical array of numerous, single point optical fibers 302 appearing approximately flush with the profile of a vertical support structure 301. The opto-electronics packages 304 are indicated by the symbol "E" and the multiplexer 305 is identified as "MUX" with output 306 to an appropriate processor/display such as shown at 410 of Fig. 4. The optical fiber used in an embodiment of the present invention is a 1-mm, step index plastic fiber with a numerical aperture, *NA*, of 0.51, a core refractive index, $\eta_{co}$, of 1.492, a cladding refractive index, $\eta_{cl}$, of 1.402, and an attenuation of < 0.20 dB/m. (Industrial Fiber Optics, Inc. 1999). Other optical fibers (either plastic or glass) with different characteristics may serve as well.

Refer to Fig. 4, a block diagram 400 of a single sensor "module" and related energy sources, processors, controls and display used in an embodiment of the present invention. For clarity, the multiplexer 305 of Fig. 3 is not shown in Fig. 4. Each optical fiber 302 is part of an array (as shown in Fig. 3) inserted in a vertical support structure 301 and connected to its own optical coupler 403. Each optical coupler 403 is also connected to a multiplexer 305 for use with common source illumination circuitry 404, 405, processing circuitry 406, 407, 408, 409, and processor/display 410. In application

specific embodiments, the processing circuitry may be embodied in the processor/display 410. In one embodiment of the present invention, the components 406, 407, 408, 409 may be incorporated on a printed circuit board internal to the processor display 410 or in an alternative embodiment they may be located within the probe assembly along with the other components 403, 404, 405.

The light source 405, typically an LED, is energized using a signal generator 404. This signal is passed through the multiplexer 305 to each of the optical couplers (splitters) 403. The return signal from the end of the optical fiber 302 is fed from the optical splitters 403 to the multiplexer 305 from which it is sent to the optical receiver 406, typically a phototransistor. The signal from the optical receiver 406 is sent to a high pass filter 407 to attain a "cleaner" signal which is then amplified by an amplifier 408 before passing to a detector 409 as input to a processor/display 410. The display may also contain control features, such as a keyboard for use by an operator in calibrating or operating the system 400. The multiplexer 305 permits each of the optical fibers 302 and their associated optical splitter 403 to share common source 405 and processing 406, 407, 408, 409 devices in a pre-specified sampling sequence.

Refer to Fig. 6 illustrating a typical commercially available optical coupler 403. The optical fibers 302 are stripped of cladding as at 607 within a coupling medium 606 that is encased in a light tight case 605. This enables energy impinging on each of the two fibers of the optical splitter 403 to be "shared" for purposes of both transmitting and receiving light energy. Light energy entering, for example, Port 2 602 is divided in half, with equal components exiting through Ports 3 603 and 4 604. Virtually no light entering Port 2 602 exits through Port 1 601. The device functions similarly for light entering any of the four ports 601, 602, 603, 604. The optical coupler 403 permits a single optical fiber 302 to act simultaneously as a receiver and transmitter of light energy. An optical receiver 406 (phototransistor, photo-diode or similar device), designated as a phototransistor in Fig. 4, is connected to one port of the splitter 403. In one embodiment of the present invention, a light source 405, shown as an LED in Fig. 4 and typically emitting visible (660-nm) red light, is connected to another port of the splitter 403. In an embodiment of the present invention as represented in Fig. 4, the last port is a dark termination 411 implemented by covering the aperture of the port with black plastic tape

(not shown separately) or otherwise providing an optically non-reflective termination. If referencing to Fig. 6, Port 3 603 is connected to the light source 405, Port 4 604 is connected to the optical receiver 406, Port 2 602 is terminated in the vertical support 301, and Port 1 601 is a dark termination 411, e.g., covered with black plastic tape thus providing a non-reflective termination. All optical fibers 302 inserted in the vertical support 301 may be configured similarly.

Since the optical fibers 302 may be exposed to some degree of ambient light when submerged in shallow water, pickup of background light along with the reflected light from the light source 405 would also be sensed by the optical receiver 406 and interfere with accurate scour depth measurement. There are at least two potential solutions to eliminate this interference.

Refer to Figs. 4 and 5. Using a light source 405 operating at a wavelength different from that of ambient light and appropriate optical bandpass filtering 407 at the photo sensor (receiver) 406 eliminates interference from the ambient light.

In one embodiment of the present invention, the time-varying intensity of natural ambient lighting is exploited. In most circumstances the intensity of natural ambient light tends to vary relative slowly with time (e.g., diurnal cycle, passage of clouds, etc.). To eliminate the interfering effects of ambient lighting, a 3-kHz square wave source 404 is used to modulate a visible light source 405, typically an LED. The signal received by each phototransistor (receiver) 406 is sent to a high-pass filter 407, thus eliminating any of the low-frequency components of the signal and permitting further analog processing of the received 3-kHz signal. This filtered signal is forwarded to an amplifier 408 and peak rectified in a detector 409, resulting in a DC voltage proportional to the intensity of the received signal. The output of the peak rectifier 409 is digitized using a 16-bit PCMCIA A/D card (not shown separately) as may be installed in a processor/display 410 such as a laptop computer, desktop computer, or a dedicated application specification processor. The subsequent data stream is processed, stored and may be displayed in real time on the display associated with the processor/display 410. Values suitable for use with this embodiment of the present invention include at V1 a 10-Volt P-P 3-Khz generator, at V2 a 15 V power source, a red light LED 405, a phototransistor 406, an 1N914 diode, resistors having values as follows: R1 = 470Ω, R2 = 20 KΩ, R3 = 4.7 KΩ,

R4 = 60 KΩ, a “variable resistor” or “potentiometer” VR1 = 47 KΩ, and capacitors having values: C1 = .01 μF, C2 = 0.047 μF.

In one embodiment of the present invention, the data acquisition, processing and display software is written in *LABVIEW*®, a GUI-based language. Other convenient or appropriate computer language may be employed. Custom displays or display formats suitable for use on existing CRTs or LCDs may be developed for clear indication of scour conditions. For example, Fig. 7 depicts a dual display 700 suitable for use with a personal computer. It includes a vertical “thermometer-like” display 701 to show the dynamic change in scour level and a numeric display 702 to give an absolute or relative indication of scour depth in engineering units, accurate to the spatial resolution, i.e., the separation of optical fibers 302 in the sensor 300 of Fig. 3. Further, an alert function may be programmed into the processor to indicate when scour has reached a critical level such as displayed at the arrow 703.

Refer to Fig. 9. Depending on implementation specifics, embodiments of the present invention may have the optical receiver 406, source 405 and splitters 403 replaced with an optical power meter 901 that measures the reflected photonic power present in an optical path. A power meter 901 provides a more sophisticated (and expensive) implementation that monitors the power of both the transmitted and the reflected optical signal while producing an output proportional to the normalized reflected power. This embodiment also functions under the principle of changing reflectance levels at the end of an optical fiber 302 as a function of a change in the refractive index contrast at the boundary *ab* of the optical fiber path and the overlying sediment or water column. If the optical path terminates into saturated sediment, there will be a specific and measurable level of reflectance. If the terminal end of the optical path is terminated, instead, into water (as would occur during scour) a different level of reflectance is measured. By noting the difference between reflectance levels occurring with sediment and water, scour may be dynamically monitored. When using an optical power meter 901, the power meter 901 may be located “high and dry” on the shoreline and coupled to the fiber scour sensor 300 by a series of optical fibers 302, or via a single optical fiber 302 and fiber multiplexer 305 located in the submerged scour probe 300.

Refer to Fig. 8. With the appropriate hardware, an embodiment of the present invention may be implemented using a directly connected optical or metallic umbilical cable 803. Additionally an embodiment may be implemented with a radio, ultrasonic, or other form of remote telemetry (not shown separately) to transmit scour status from the buried optical probe 300 to an on-shore monitoring and data storage system such as that described as elements 406, 407, 408, 409 and 410.

In the case of a highly saline environment, e.g., seawater, the radio telemetry method is impractical because of the losses suffered by the radio signal propagating through a lossy medium. Additionally, an implementation using batteries and a wireless means (all not shown separately), such as a radio or submerged acoustic telemetry link, is most suitable for shorter-term applications in which the probe is either disposable or retrievable for refurbishment and replacement of batteries. An umbilical cable-based system as depicted in Fig. 8 is intended primarily for long-term or permanent monitoring situations where the umbilical cable 803 may be easily and more permanently installed and used in electrically lossy environments. Further, the sub-system that receives and processes sensor data may be operated in a more benign environment than the probe 301, 302 itself.

In one application, an embodiment of the present invention is buried in river bottom sediments 802 below water 801 in a body of water being monitored for scour. It is emplaced via a heavy anchor 804 at a point below the maximum expected depth of scour. Primarily, an embodiment of the present invention is designed for installation by "air jetting" or "hydro jetting". Alternatively, it may be installed in softer sediments by being "pile driven" or hydraulically forced into the sediment 802. In one embodiment of the present invention, the top of the installed probe is "surveyed in" relative to a local survey benchmark.

Depending on the desired implementation, output signals of an embodiment of the present invention may be further multiplexed to monitor a distributed array consisting of numerous probes (each having a vertical array of optical fibers 302 as shown in Fig. 3) installed in close proximity to a structure or sediment field of interest.

There are advantages to the implementation of an optical time domain reflectometer for scour monitoring:

can operate in brackish, saline or otherwise electrically conductive waters or other fluids,

able to operate in environments where magnetic or metallic transmission lines may interfere with data taking, and

media does not have to be transparent nor translucent for operation.

Numerous industrial, commercial, and military instrumentation and measurement systems can take advantage of this technique. Some potential applications include:

material depth and clarity change measurement/monitoring in industrial tanks such as plating tanks,

clarity monitoring and control of weirs,

environmental monitoring in conductive environs, e.g., between layers of double layer underground storage tanks,

monitoring of oil reservoirs of internal combustion engines to detect when oil needs to be added and when an oil change is necessary,

bridge scour measurement/monitoring,

navigation channel sedimentation monitoring,

dredging spoils stability monitoring, and

coastal sediment monitoring.

Although only a few exemplary embodiments of this invention have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of the invention. Accordingly, all such modifications are intended to be included within the scope of this invention as defined in the following claims. In the claims, means-plus-function clauses are intended to cover the structures described herein as performing the recited function and not only structural equivalents, but also equivalent structures. Thus, although a nail and a screw may not be structural equivalents in that a nail employs a cylindrical surface to secure wooden parts together, whereas a screw employs a helical surface, in the environment of fastening wooden parts, a nail and a screw may be equivalent structures.

The abstract of the disclosure is provided to comply with the rules requiring an abstract, which will allow a searcher to quickly ascertain the subject matter of the

technical disclosure of any patent issued from this disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. 37 CFR § 1.72(b). Any advantages and benefits described may not apply to all embodiments of the invention.